iSAT Environments

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The Environmental Characteristics

- Orbits
- Orbit Transfers
- Lighting and Thermal
- Radiation
- Spacecraft Charging
- Micro-Meteoroid Orbital Debris (MMOD)
- Gravity Gradient Torques

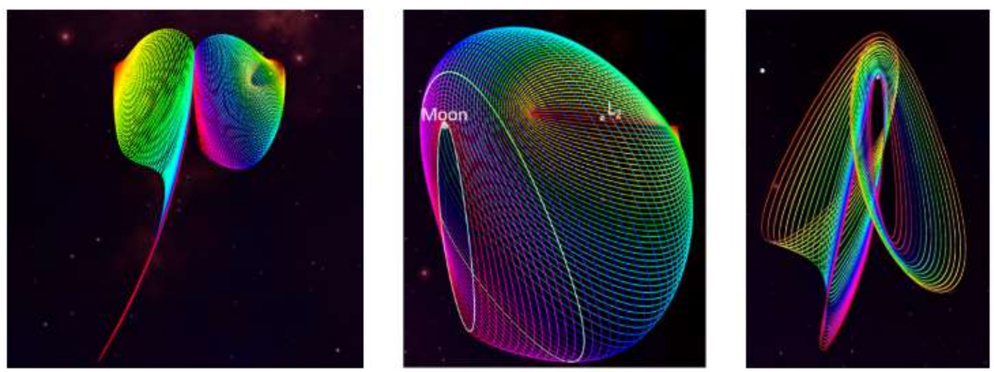
Orbits: LEO and GEO

	LEO	GEO
Stability	Orbits >600 km tend to have very long lifetimes (Hubble ~569 km), all subject to eventual decay and gravity gradient torques ISS altitude of 400 km has significant drag-induced decay	Decay and gravity gradient torques not a factor
Period (hr)	~1.5	24 (23.934)
Perigee/apogee (km)	~400-800 + Earth radius	35,786 + Earth radius
Inclination (deg)	0-180 (ISS 51.64; Hubble 28.5; Cape Canaveral 28.47; Sun-Sync 98)	0

[Wertz], [Montenbruck]

Orbits: Gateway

- Latest information: Near rectilinear halo orbit (NRHO) [Crusan et al.]
- Subsets of the EML1 and EML2 halo orbit families (orbits Earth at same rate as Moon)
- “The NRHOs are defined as the subsection of the halo orbit family possessing stability indices all within some small bound surrounding ±1 and with no stability index that is significantly larger in magnitude than the others.” [Zimovan]
  - Marginally stable if stability indices less than magnitude 1



(a) The L_1 and L_2 southern halo families of orbits in configuration space.

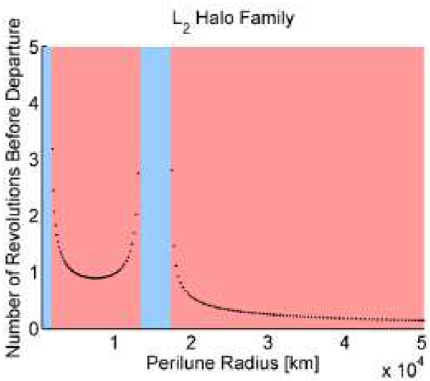
(b) Zoomed-in view of the L_2 halo family delineating the bounds of the NRHOs in white.

(c) Zoomed-in view of the L_1 and L_2 NRHOs.

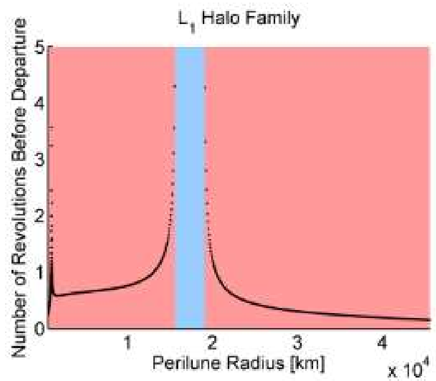
[Zimovan]

Figure 2. The L_1 and L_2 halo orbit families and the NRHOs.[11]

Orbits: NRHO Characteristics



(a) Time constant as a function of perilune radius across the L_2 NRHOs.



(b) Time constant as a function of perilune radius across the L_1 NRHOs.

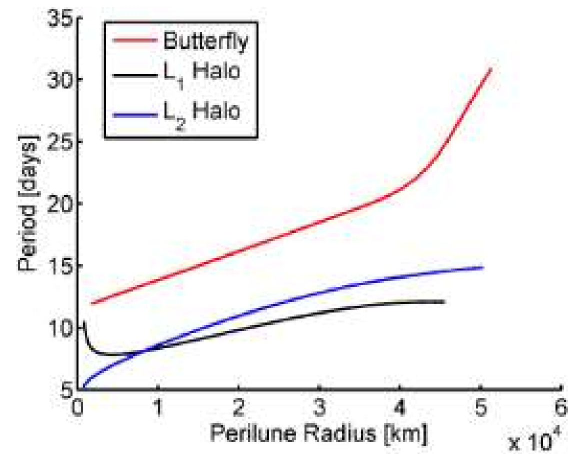


Figure: Time constants for NRHOs that are unstable (left) and period length variation with perilune radius (right) [Zimovan]

	Note: Halo orbit
Stability	Marginally stable (linear approximation)
Period (days)	6 - ~10
Perilune (km)	100– 15600 + Lunar radius
Inclination (deg)	“Approximately polar”

Orbits: SEL2

- Approximately ~.01 AU beyond Earth, orbits Sun at same rate as Earth
- Instability naturally removes uncontrolled debris (unlike L4, L5)
- All bright sources (Sun, Earth, Moon) always in same celestial hemisphere

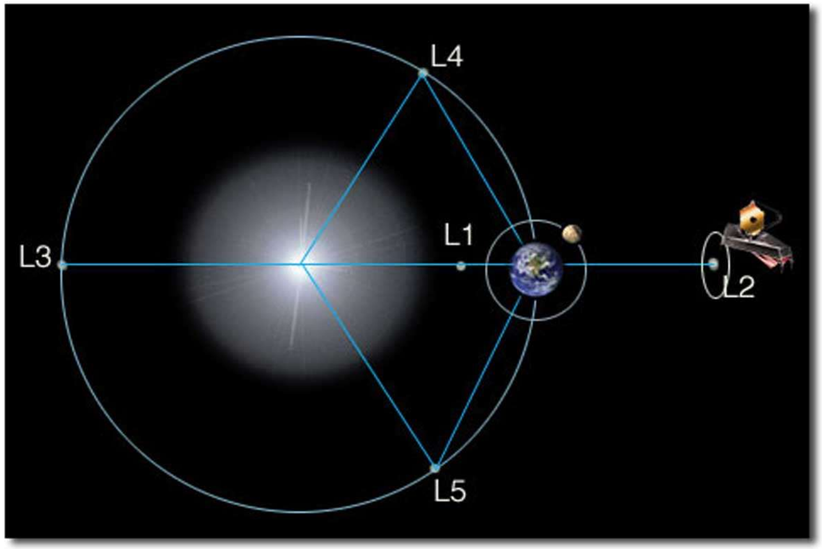


Image credit: stsci.edu

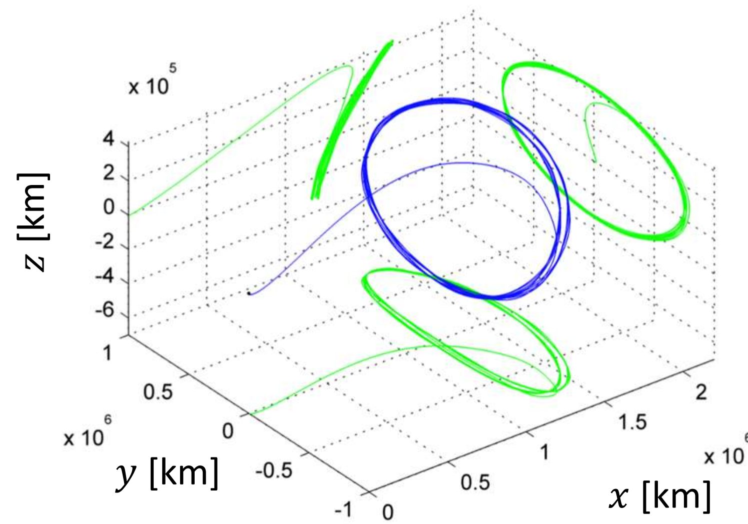
	Note: Halo orbit
Stability	Unstable along Sun line of LVLH frame (linear approximation)
Period (months)	~6, depends on amplitude
Periapsis/Apoapsis (km, to SEL2)	For JWST: 250,000/832,000
Inclination (deg)	"Approximately polar with respect to ecliptic plane"

Orbits: SEL2 Halo Stability

- SEL1 and SEL2 are saddle points and objects will drift away along Sun line (x-axis) but oscillatory in orbit direction (y-axis) and out of the ecliptic plane (z-axis)
  - e-folding time around 23 days
  - For example, JWST must perform a ΔV correction of 10-20 cm/sec every 20-30 days [Dichman]

Orbits in L2:

- *Lyapunov Orbit*: periodic orbit restricted to move in the plane defined by primary bodies
- *Lissajous Orbit*: a general quasi-periodic orbit with a component that is normal to the primary body's plane of motion
- *Halo Orbit*: A type of Lissajous orbit that is periodic repeating every ~6 months depending on amplitude

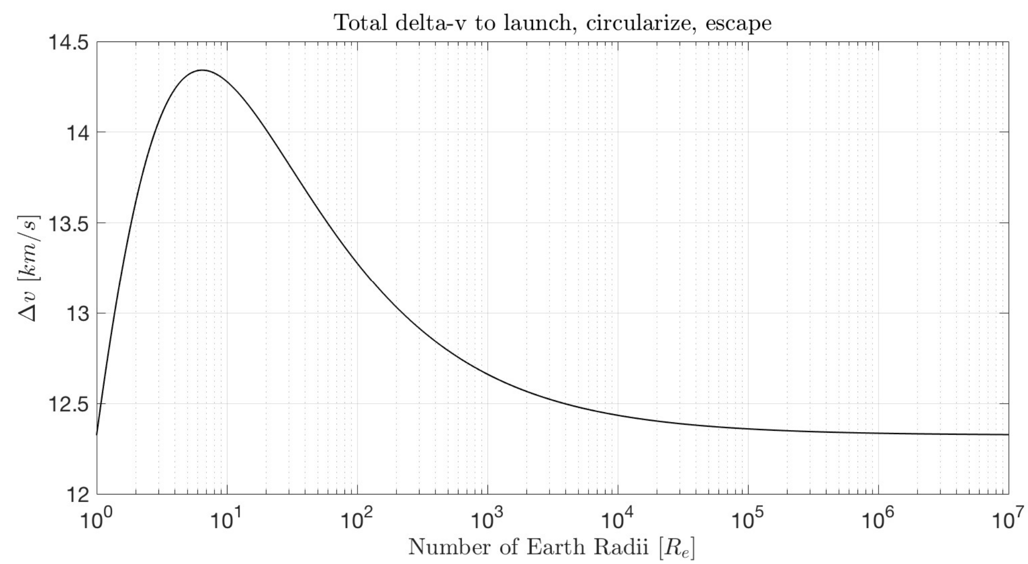


Halo orbit in L2 propagated for 4 years
(Origin is defined as center of Earth)

[Hechler]

Transfers: Escape vs. Circularization Altitude

- ΔV presented is the change in velocity needed to launch due East from Earth's surface, circularize, and then reach Earth escape velocity
  - Launching due East maximizes throw mass to a given altitude
  - Circularizing in GEO requires highest ΔV
  - If telescope mass is much greater than assembler-servicer mass, moving the telescope between GEO and SEL2 is expensive

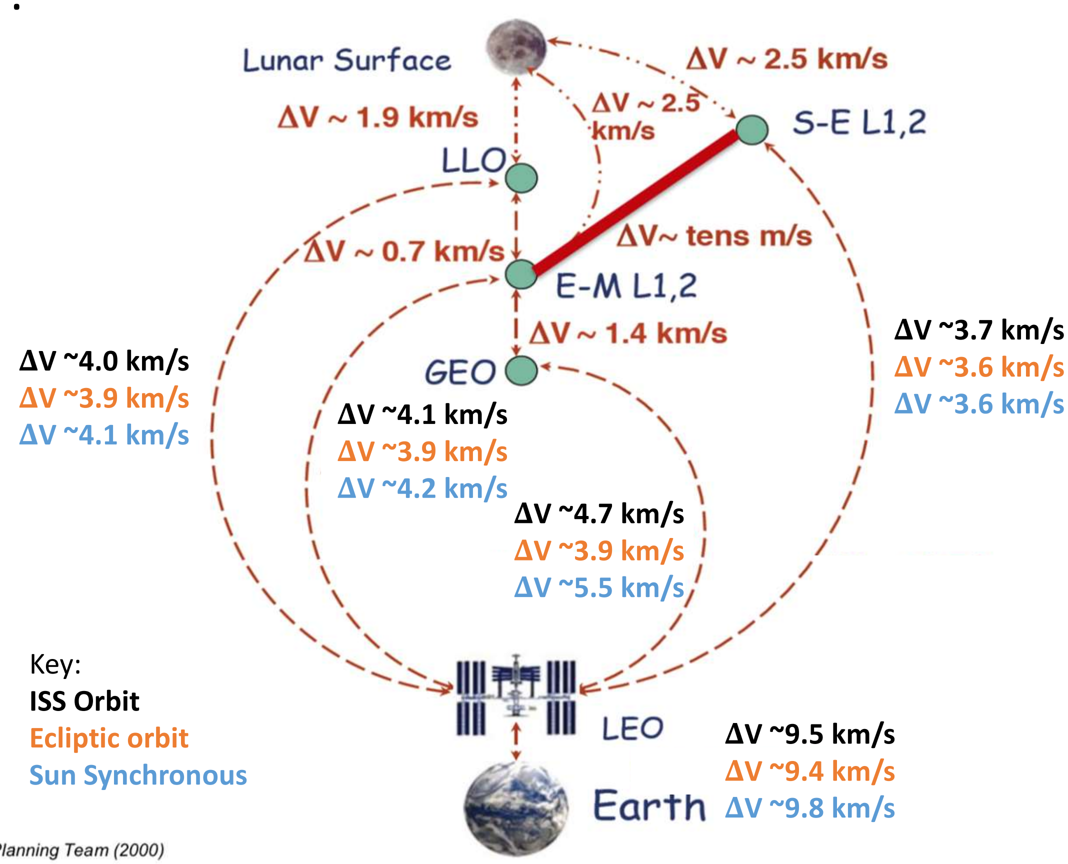


- Launching to ISS at 51.6° reduces throw mass and requires additional plane change to get to SEL2
  - Raise apogee at perigee (in LEO)
  - Change plane and circularize at apogee (at SEL2)

Transfers: ΔV Roadmap from Earth

- Three LEO orbit costs represented :
  - ISS orbit (existing logistics)
  - Ecliptic orbit (high throw mass)
  - Sun Synchronous (Restore-L)

- Notice
  - Low ΔV to go from EML1,2 to SEL2
  - High ΔV to launch to GEO then transfer to SEL2



NASA's Decade Planning Team (2000)

Lighting and Thermal: Considerations

- Earth albedo (reflected solar irradiance)
  - Fraction of solar irradiance, higher over land, clouds, and ice/snow
  - Generally higher with latitude

- Solar irradiance
  - Inverse square law
  - 7% UV, 46% visible, 47% near IR

- Earth/Moon irradiance
  - Blackbody radiation of non-albedo absorbed energy

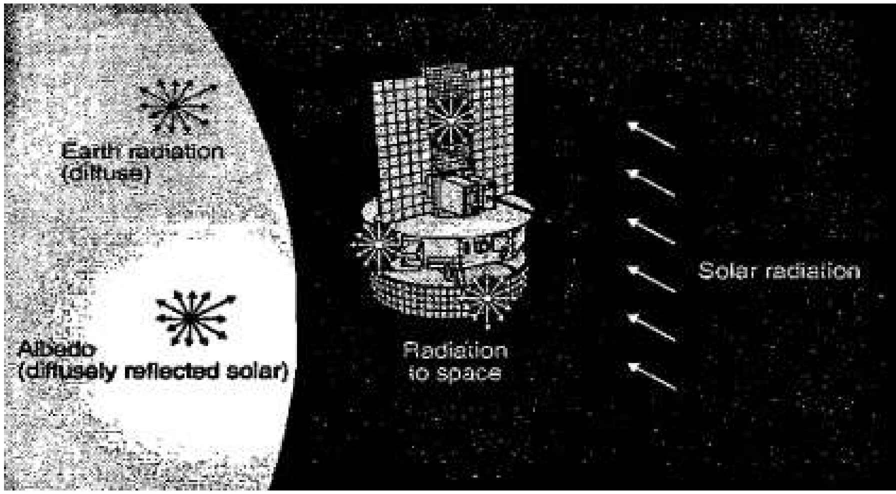


Figure: Cartoon of sources of thermal influx [Wertz]

Lighting and Thermal: Near-Earth Thermal

- 120 km to 600 km within the thermosphere, increase in temperature with altitude due to trapped UV radiation
  - Peak ~200-250 km, ~600-1200 K over solar cycle
  - Heating due to extreme UV radiation a concern
  - Drag-induced orbital decay strongly affected by solar cycle

Orbit Inclination (deg)	Angle of Sun Out of Orbit Plane (deg)	Emitted Radiation (W/m^2)		Albedo (percent)	
		Min	Max	Min	Max
0–30	0	228	275	18	28
	90	228	275	45	55
30–60	0	218	257	23	30
	90	218	257	50	57
60–90	0	218	244	23	30
	90	218	244	50	57

Figure: Earth-emitted thermal sources [Wertz]

Lighting and Thermal: Eclipses

- Period of *eclipse* exists due to Earth and/or Moon obstructing light
  - LEO: ~1/3 of time in eclipse, but depends on inclination and orbit variety
    - Eclipse length approximately constant, but percentage decreases with altitude
    - Worst case when Sun in orbit plane: ~31.7%
    - ISS: Best case of 0% eclipse
    - Equatorial: Best case of ~16.3% eclipse
  - Φ : eclipse duration angle
  - ρ : Earth angular radius
  - β_S: angle of Sun above/below orbital plane

$$\cos(\Phi/2) = \cos\rho / \sin\beta_S' = \cos\rho / \cos\beta_S$$

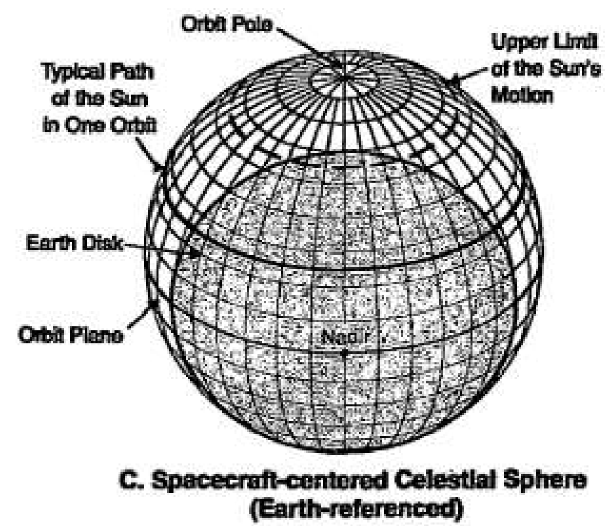
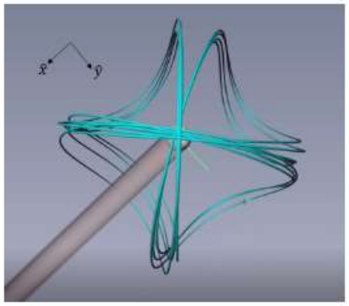


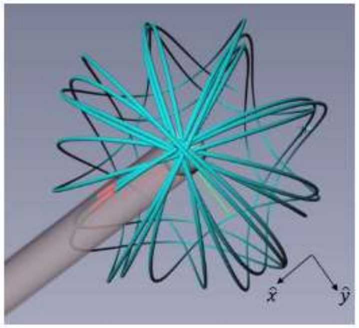
Figure: Calculation of eclipse angle [Wertz]

Lighting and Thermal: Eclipses

- Solar Flux: 1360 W/m^2 @ 1 AU, 1330 W/m^2 @ 1.01 AU
- LEO
  - Eclipse duration less variable at low inclination, “cold side” for sun-synchronous, high inclination may have long periods of no eclipse
- GEO
  - 23.5 deg inclination relative to ecliptic plane
  - Equinox cold season: eclipse season of 3 weeks with 72 min eclipses
  - <1% of incoming energy is due to Earth albedo + blackbody [Wertz]
- SEL2
  - Webb’s halo orbit assures it remains outside of Earth/Moon shadow
- NRHO (see figures)
  - Eclipse depends on NRHO parameters (e.g., insertion date), can use synodic resonance to avoid lunar eclipse
  - Can also avoid Earth eclipse if apolune occurs during full moon



(b) A 4:1 synodic resonant NRHO shown looking down the z-axis onto the x-y plane.



(b) A 9:2 synodic resonant NRHO shown looking down the z-axis onto the x-y plane.

Figure: NRHO avoiding eclipse (top) and hitting eclipse (bottom) [Zimovan]

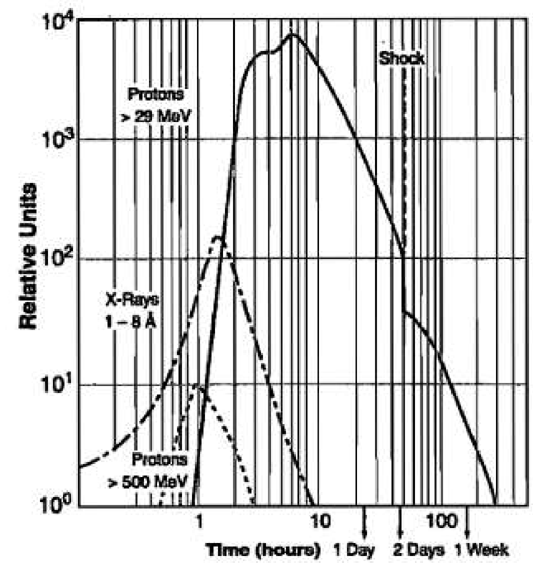
Lighting and Thermal: Summary

- SEL2 and NRHO provide constant sunlight
  - Eclipse most frequent in LEO
- All comparable distance from Sun
- Greater variety of significant thermal factors in LEO

Location	Dominant Thermal Contributors	Fraction Solar Constant from 1 AU	Eclipse Fraction
LEO	Solar irradiance, albedo, Earth blackbody	1	worst case (1/3), varies
GEO	Solar irradiance	~1	worst case near equinox (0.05)
SEL2	Solar irradiance	0.98	can design to be 0
Gateway (NRHO)	Solar irradiance	~1 (minor variation with lunar orbit)	can design to be 0

Radiation: Sources

- Van Allen belts
  - Particles captured from solar wind and cosmic rays
  - ~500 km to 58,000 km
- Solar particle events, Solar energetic particles
  - Only a few SPEs per year, activity peaks near sunspot maximum
  - 11 year solar cycle
  - Figure shows typical SPE
- Cosmic rays
  - Cause single-event phenomena in electronics
    - Single-event burnout
    - Single-event latchup
    - Bitflip



Time evolution of SPEs, observed from Earth [Wertz]

[Jursa], [Wertz], [Leach]

Radiation: Near-Earth Environment

- Interaction with Earth’s magnetic field produces complex radiation environment
- Van Allen belts trap energetic particles near Earth
- Long magnetotail formed on leeward side of Earth
  - Denser plasma sheet, with neutral region
  - Magnetosheath on boundary of tail
- Analogous to aerodynamic bow shock

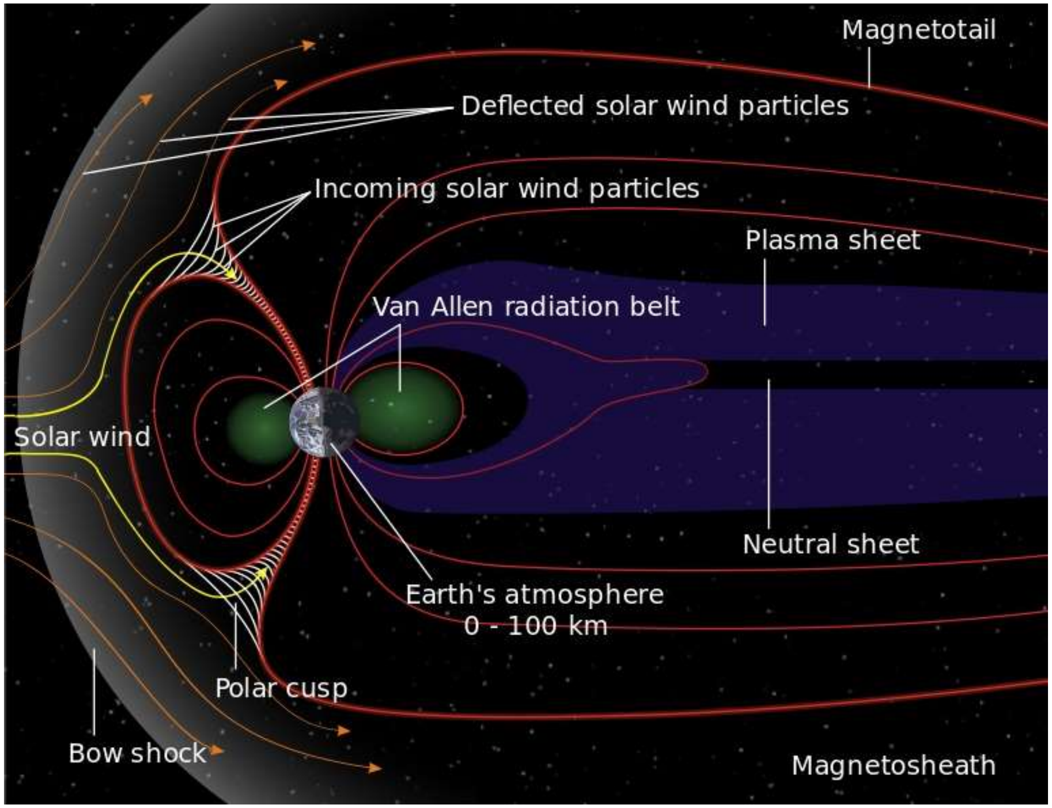


Image credit: www.nasa.gov

Radiation: Terminology

- 1 *rad* = .01 J/kg of radiation absorbed
  - (rem/Sv are measures of biological impact)
- "A crude measure for damage done by penetrating energetic radiation is radiation dosage which is measured in rads" [Jursa]
- *Radiation dose*: rads/yr, a measure of dosage per year in a certain orbit, using a radiation and shielding model. Protons + electrons + *bremsstrahlung* (interaction with shielding material)

Radiation: LEO/GEO

- Van Allen belts: electrons and ions with energies mostly above 30 keV, usually >1000 – 6000 km
- Solar particle events: rapid increases in release of energetic particles, several hours to several days: a few occur per year
- Near-Earth: 83% protons, 13% alphas (He nuclei), 1% larger nuclei, 3% electrons
- In GEO, lower-energy ions harm space systems differently than penetrating radiation, e.g. heat loads of up to 0.5 W/m2, degrading paints/glass [Wertz]

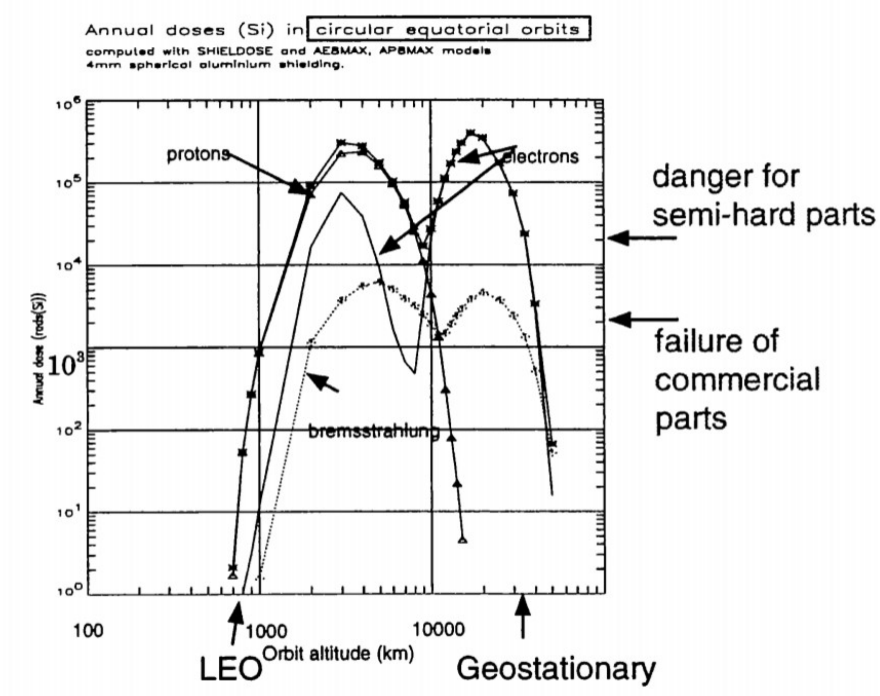


Figure: Radiation dose for equatorial orbits [Daly]

Radiation: Gateway and SEL2

- Both exposed to SPEs and cosmic rays
- Must pass through radiation belts en route to destination
- "…full exposure to galactic cosmic heavy ions and particles from solar events…" [Barth]
  - Due to large radius of halo orbit about SEL2, S/C has periodic exposure to magnetotail and magnetosheath

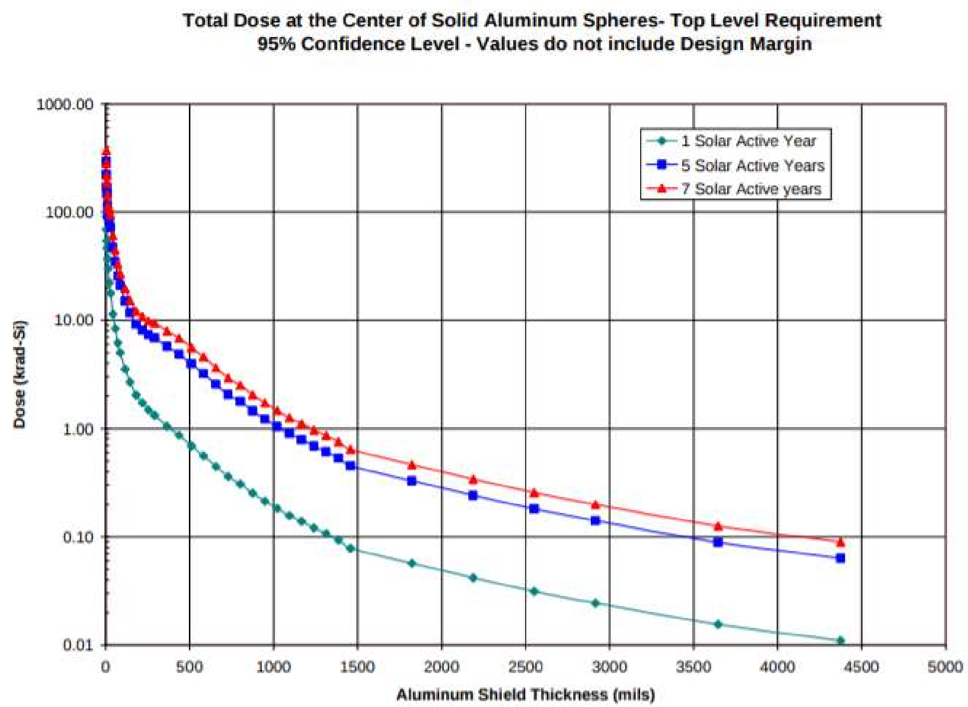


Figure: Radiation dose predictions for JWST at SEL2 [Barth, 2000]

Spacecraft Charging

- Spacecraft charging occurs when charged particles cause dangerous differentials between spacecraft components that can damage electronics during discharge
- Charging depends on the relative environment: also common for high latitude, low altitude (auroral electrons)
  - Not a concern for lower equatorial orbits
- Magnetotail extends up to 1000 Earth radii on leeward side of Earth
  - Resulting spacecraft charging can extend to GEO
  - GEO charging between “midnight and dawn” longitudes

[Wertz]

Solar Pressure: Considerations

- *Radiation pressure*: pressure exerted on any surface by exchange of momentum with EM field
  - Solar flux obeys the inverse square law → so does solar pressure
- Acceleration due to solar radiation pressure: $a_R \approx -4.5 \times 10^{-6} (1 + r) A/m$
  - A: cross-sectional area
  - m: satellite mass
  - r: reflection factor (~.4 for diffuse reflection)
  - Higher acceleration for low ballistic coefficient satellites
  - More significant than drag above ~800 km
- Will cause angular momentum build-up due to CP-CM offset
  - Roughly 1/3 propellant used for dumping angular momentum and 2/3 for halo orbit maintenance

[Wertz, Barth, McInnes]

MMOD: Overview

- *Orbital debris*: Any non-operational human-made object in space
  - Rocket bodies, separation devices, etc.
  - ~15,000 currently catalogued
- *Passive collision avoidance*: reduce cross section and add shielding
- *Active collision avoidance*: modify orbit
- Passive good for <5 mm, active possible for >10cm [Pulliam]
  - 5 mm-10 cm most dangerous

Breakup Debris	40%	Spacecraft	30%
Rocket Bodies	18%	Operational Debris	12%

Deliberate Breakup	30%
Propulsion System Malfunctions	31%
Unknown Cause	28%
Battery	4.5%
Aerodynamics	6%
Collision	0.5%

Figure: Approximate categorization of orbital debris and its origin [Wertz]

MMOD: as a Function of Time and Altitude

- Growth in catalogued objects, with density spikes for low LEO, MEO, GEO

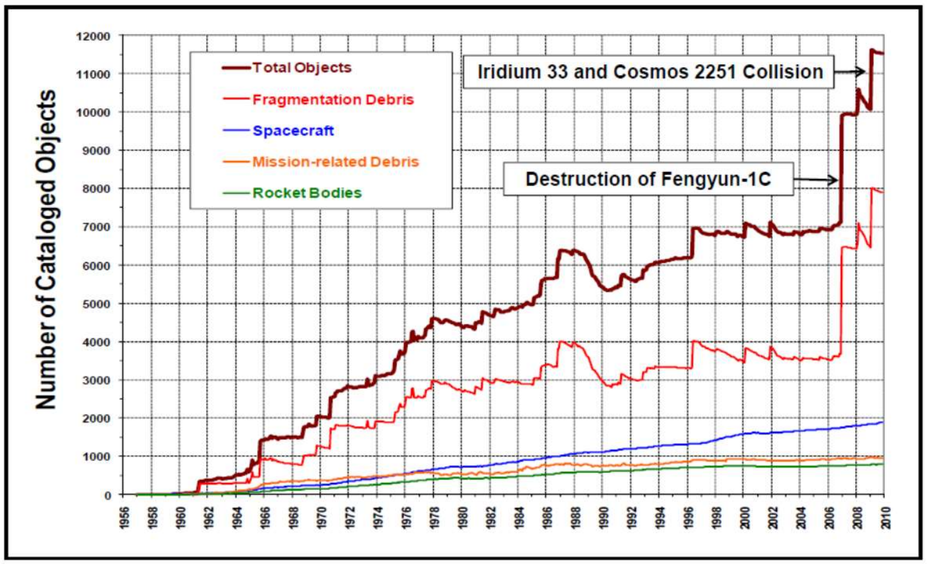


Figure 1 – Growth of the cataloged LEO space object population shows a large increase since 2007 due largely to two significant events.[5]

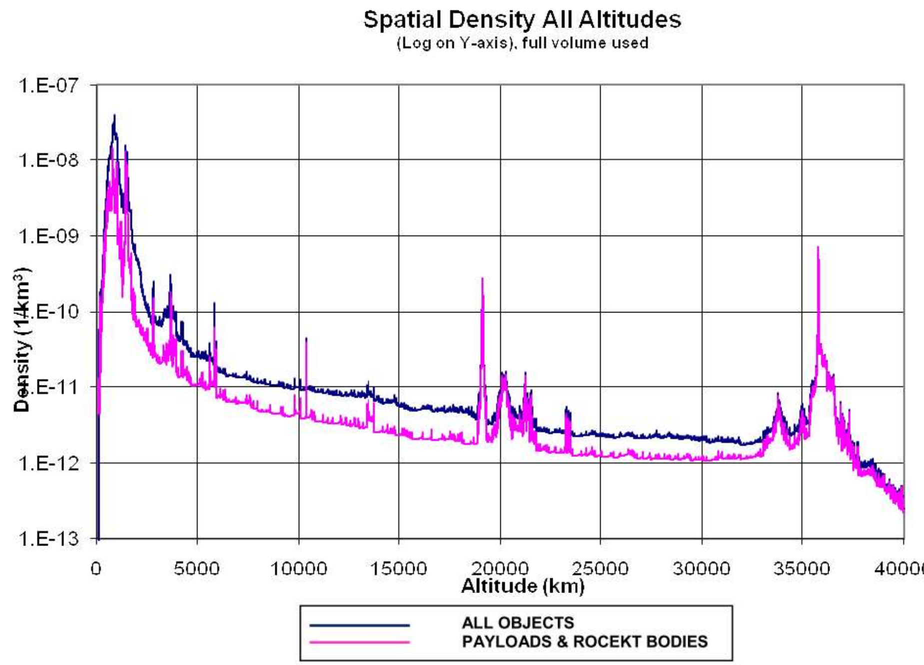


Figure 2 – The spatial density of cataloged debris shows highest levels in LEO with secondary peaks at semi-synchronous orbit and GEO.[6]

Figure: MMOD growth (left) and spatial density (right) [Pulliam]

MMOD: as a Function of Size

- Risk exists mainly in the 5mm to 10 cm range
- Largest flux is small debris, which can be effectively shielded

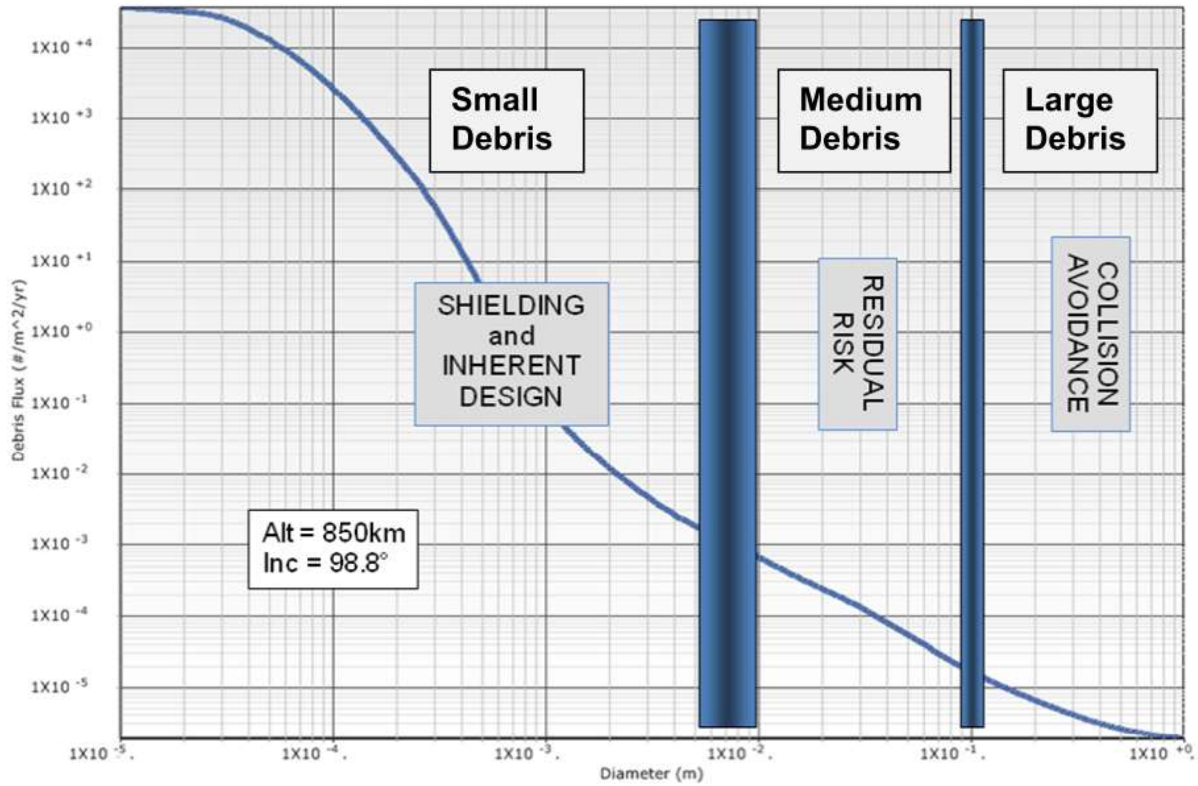


Figure 3 - The vast majority of debris can be either shielded against or avoided, but no countermeasure currently exists for medium (5 mm – 10 cm) debris.

[Pulliam]

MMOD: LEO

- 9-10 km/s collision difference average, up to 14 km/s for eccentric/retrograde orbits
- Natural cleansing of lower orbits through drag
- LEO spatial density ~1-2 orders of magnitude more than GEO

Altitude (km)	Collision Probability per Year		
	Trackable	1 cm diameter	1 mm diameter
300	10^{-6}–10^{-5}	10^{-4}–10^{-3}	10^{-2}–10^{-1}
400	10^{-5}–10^{-4}	10^{-4}–10^{-3}	10^{-1}–1
500	10^{-5}–10^{-4}	10^{-4}–10^{-3}	10^{-1}–1
600	10^{-5}–10^{-3}	10^{-4}–10^{-2}	10^{-1}–1
800	10^{-4}–10^{-3}	10^{-3}–10^{-2}	10^{-1}–1
1,000	10^{-4}–10^{-3}	10^{-3}–10^{-2}	10^{-1}–1
1,200	10^{-4}–10^{-3}	10^{-3}–10^{-2}	10^{-1}–1
1,500	10^{-5}–10^{-3}	10^{-3}–10^{-2}	10^{-1}–1
2,000	10^{-6}–10^{-5}	10^{-5}–10^{-3}	10^{-2}–10^{-1}

Figure: Collision risk by size and altitude [Wertz]

MMOD: GEO

- Collision risk and speed (100-500 m/s) is lower than in LEO
- But,
  - Assets tend to be of higher value
  - Debris field growth is dominant along orbit track
  - Many satellites share the same orbit track
  - Larger consequences for collision because of proximity of satellites in GEO band [Pulliam]

MMOD: Gateway and SEL2

- A few manmade satellites exist at SEL2, and EML2
- Natural orbital debris is self-flushing due to instability
- “Spacecraft at SEL2 will be subject to bombardment by meteoroids, but owing to the limited and transient residence of manmade objects in this region, artificial space debris should not pose a collision hazard for many years.” [Evans]

MMOD: Gateway and SEL2

- Meteoroids either *sporadic* or members of known *streams*
- Cislunar space subject to micrometeoroids, SOA modeling done by NASA MEM tool [McNamara]
- SEL2 well-characterized
    - Sporadic generally uniform from six unique directions from unknown sources
    - Streams generally traced to known comets [Evans]

SEL2 Meteoroid Characteristics

- SEL2 has been well-characterized in preparation for Webb, other missions

Table 7.2 Meteor streams known to produce enhanced or storm level activity.

Stream	Radiant		Speed (km s^{-1})	Time of max activity
	RA	Declination		
Quadrantids	230°	+49°	41	Jan 03
κ Cygnids	286°	+59°	25	Aug. 18
Lyrids	271°	+34°	49	Apr. 22
Draconids	262°	+54°	20	Oct. 09
Perseids	46°	+58°	59	Aug 13
Leonids	152°	+22°	71	Nov. 17-18

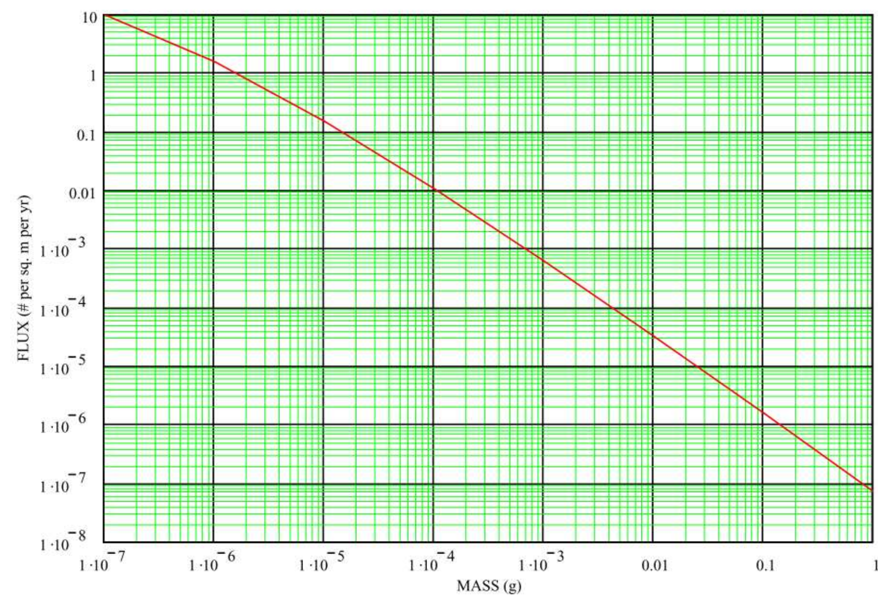
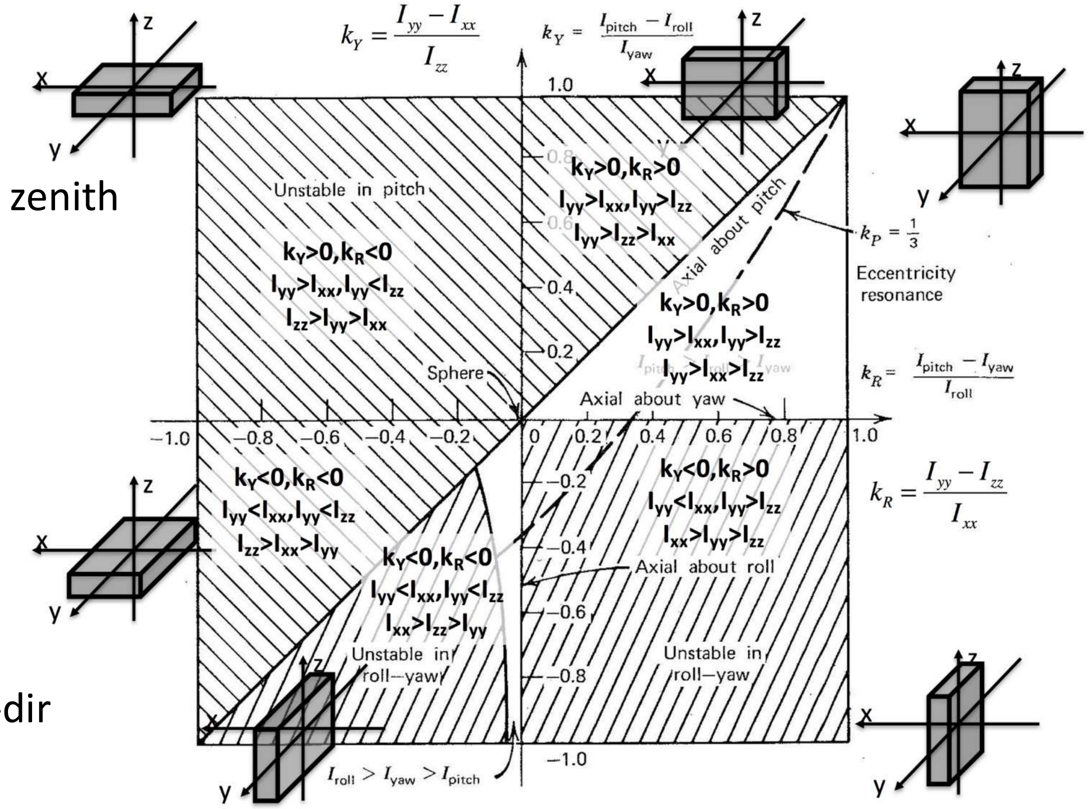


Figure 7.1 Sporadic meteoroid flux as a function of mass (Grün Equation).

Figure: Stream (left) and sporadic (right) meteoroids for SEL2 [Evans]

Gravity Gradient Torques: LEO

- Torques in Local Vertical, Local Horizontal (LVLH) Frame
  - X-dir is ram, y-dir is cross track, z-dir is zenith
  - Only significant in LEO



- Torques in LVLH frame

$$\vec{M} = 3n^2\left\{-(I_{yy} - I_{zz})\theta_1\hat{i} - (I_{xx} - I_{zz})\theta_2\hat{j} - 0\hat{k}\right\}$$

- Only stable orientation is
  - Max Moment of Inertia (MoI) about y-dir
  - Min MoI about z-dir

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Solar Pressure: Backup

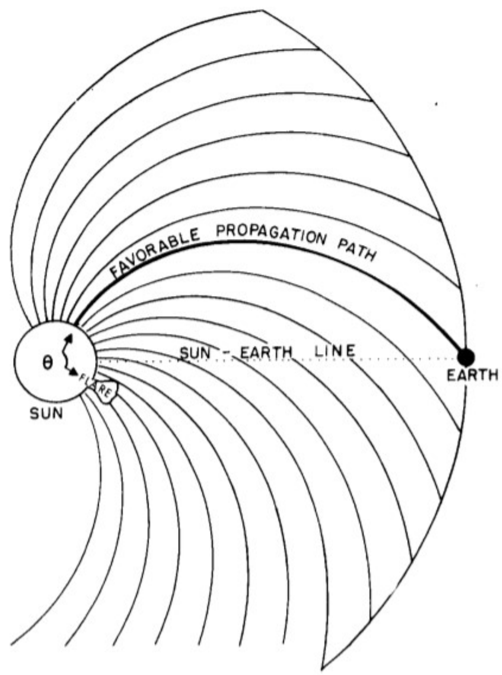


Figure: Propagation path of solar wind [Wertz]

Orbits: Backup

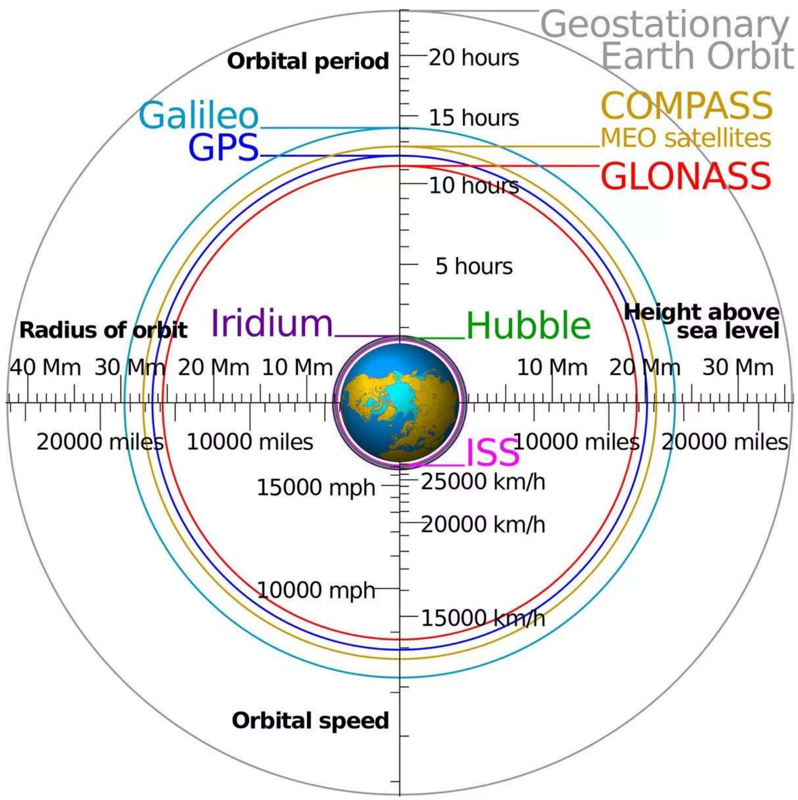
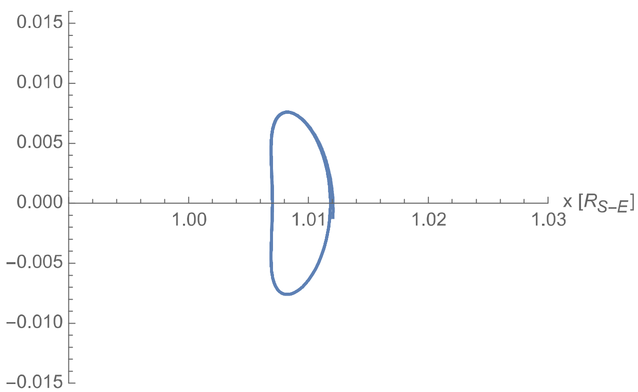


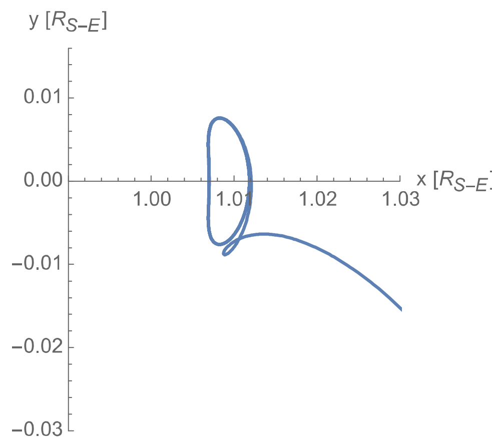
Image credit: www.spacesafetymagazine.com

Orbits: SEL2 Halo Stability

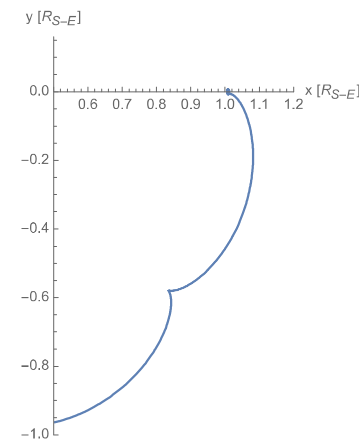
- In a rotating frame, L1 and L2 are saddle points that cause object to drift away
  - e-folding time around 23 days
  - Linear stability analysis at L2 shows that system is stable in the y and z direction, but unstable in x
- For example, JWST must perform a delta-V correction of 10-20 cm/sec every 20-30 days [Dichman]



4 months w/o upkeep



8 months w/o upkeep



30 months w/o upkeep

Note: R_{S-E} is distance between Earth and Sun